DOCUMENT RESUME

ED 246 056 TM 840 180

AUTHOR	Hunt, Earl; Lansman, Marcy
TITLE	Performance in Dual Tasks. Final Report.
INSTITUTION	Washington Univ., Seattle. Dept. of Psychology.
SPONS AGENCY	Office of Naval Research, Arlington, Va. Personnel and Training Research Programs Office.
REPORT NO	ONR-TR-84-2
PUB DATE	29 Feb 84
CONTRACT	N00014-80-C-0631
NOTE	78p.
PUB TYPE	Reports - Research/Technical (143)
EDRS PRICE	MF01/PC04 Plus Postage.
DESCRIPTORS	*Attention; *Cognitive Processes; Cognitive Style; *Computer Simulation; Computer Software; Individual Differences; Literature Reviews; Memory; *Models; Problem Solving

ABSTRACT

This project was designed to construct a single theoretical framework for the analysis of problem solving and real time "attention and performance" behavior. The model was developed as a computer program. It was designed in a similar manner to that of various problem solving simulations that use the "production system" approach. The program has been used to simulate results from choice reaction time, stimulus repetition, dual channel monitoring, and conflicting stimulus (Stroop) paradigms. Several questions arose during development of the model concerning human performance in situations requiring attention allocation. Experiments were conducted that indicated the mediation of attention allocation by stimulus frequency occurred through the automatic processing system. However, attention allocation mediated by warning signals occurred through the controlled processing system. Further studies suggested that individual differences in the ability to control attention were specific to a stimulus modality, rather than to a generalized ability to control attention. The theoretical framework developed and described here has been used as an integrative device to order the literature on individual differences in cognition, verbal comprehension, and techniques for assessing an individual's ability to memorize and recall information. (Author/DWH)

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Final Report

Contract N0001[illegible]-80-C-0631

PERFORMANCE IN DUAL TASKS

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This research was sponsored by:

Personnel and Training Research Program
Psychological Sciences Division
Office of Naval Research
Under Contract No. [illegible]
Contract Authority Identification Number, [illegible]

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TM 840180

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Technical Report No. 84-2	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Final Report Performance in Dual Tasks		5. TYPE OF REPORT & PERIOD COVERED Final Technical Report (1 April 77 - 29 Feb. 84) 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Earl Hunt and Marcy Lansman		8. CONTRACT OR GRANT NUMBER(s) N00014-80-C-0631
9. PERFORMING ORGANIZATION NAME AND ADDRESS Dept. of Psychology, NI-25 University of Washington Seattle, WA 98195		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Personnel and Training Research Programs Office of Naval Research (Code 442PT) Arlington, VA 22217		12. REPORT DATE 29 Feb 84 13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Problem solving, attention, computer simulation, choice reaction time, controlled processing, automatic processing, dual tasks, stimulus repetition, Stroop, conflicting signals, cognition, individual differences, verbal comprehension, memory, intelligence testing.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The goal of this project was to construct a single theoretical framework for the analysis of problem solving and real time "attention and performance" behavior. Such a model has been developed. It has been realized as a computer program. The program is designed in a manner similar to that of various problem solving simulations that use the "production system" approach. The program has been used to simulate results from choice reaction time, stimulus repetition, dual channel monitoring, and conflicting stimulus (Stroop) paradigms. In the

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S/N 0102-LF-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

development of the model several questions arose concerning human performance in situations requiring attention allocation. Experiments were conducted that showed that the mediation of attention allocation by stimulus frequency occurs through the automatic processing system, while attention allocation mediated by warning signals occurs through the controlled processing system. Further studies suggest that individual differences in the ability to control attention are specific to a stimulus modality, rather than due to a generalized ability to control attention.

The theoretical framework developed here has been used as an integrative device to order the literature on individual differences in cognition, verbal comprehension, and techniques for assessing an individual's ability to memorize and recall information.

FINAL REPORT

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PERFORMANCE IN DUAL TASKS

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OVERVIEW:

The goal of this project was to develop and test a model of human information processing that could be applied both to problem solving and attention allocation. Traditionally these areas of behavior are seen as being different topics. The questions we asked were (a) whether a theoretical unification was possible and (b) if it were, how the unification could be used to develop an integrated view of a wide variety of phenomena reported in the literature.

Three classes of studies were undertaken. The main one was the development of a model of human information processing. The model has been realized and tested by computer simulation. A summary of the model and its application is presented below. In order to construct the model it was necessary to make several assumptions about the nature of "allocation of attention" during real time problem solving tasks. When possible, these assumptions were supported by reference to the literature. In some cases, though, further experimentation was required. The results of these experiments and their influence on the model are also reported below.

Because the work was intended to be integrative, it was necessary to show that our theoretical ideas could be applied as organzing principles for a field of psychology, as well as being applied to predict or reconstruct the outcomes from specific experiments. The assertion that a theory is integrative cannot be proven; it can only be demonstrated by using that theory to organize a body of data. Two such organizations have been attempted; one to the literature on individual differences in cognitive performance, and one to the literature on verbal comprehension.

In addition, the implications of these organizations of the literature have been explored in three specific fields; individual assessment, verbal comprehension, and use of the theoretical model to guide in the evaluation of memory in clinical situations, including the aftermath of head injury or diseases affecting the brain. Such explorations of theoretical ideas are, by their nature, speculative. However, such speculations are an extremely important part of the total scientific effort for two reasons. They obvious one is that they point the way for future research. A less obvious but equally important role

for these explorations is that they provide a bridge between the development of highly specific basic research findings and the more integrative approach required in the design phase of human engineering studies.

The immediately following section of this report describes the simulation model, and presents a summary of the results obtained with it. The results of the experimental studies are then reported. The next section describes how the ideas present in the simulation can be used, by summarizing the conclusions of the integrative studies. The final section describes directions of future research. This includes a brief statement of work that is now being pursued, and some further comments on other research issues.

This report is intended to serve as a summary, and to provide pointers to the relevant literature. Therefore the detail of presentation is less than would be found in an archival document. References have been provided for those interested in exploring further details of all topics presented here.

THEORETICAL STUDIES

Introduction

This section of the report describes the theoretical model that has been developed, and reports several simulation studies that have been made to justify it. The model will be referred to as the Production Activation Model. It is one of a class of models that depict human thought as the activation of a pattern-action rules, or productions , a theoretical notation first introduced into psychology by Newell and Simon (1972), and since adopted by several other theorists. The Production Activation model goes beyond the original Newell and Simon model by including the use of a semantic activation network to control production execution. Anderson (1976, 1983) has introduced a similar concept in his simulation work. The present study goes beyond Anderson's in two ways; in its concern for real time aspects of thought and in the use of the concepts of channels of input (e.g. the eyes and the ears), instead of considering reaction to a generalized stimulus situation.

The Production Activation model was first sketched out in a proposal by Hunt (1981). The model was then developed as a PASCAL program, and has been used to simulate a number of results in the literature on attention and performance. Preliminary simulation studies were reported by Hunt and Pixton (1982). Hunt and Lansman (1984) present a detailed report of the final form of the model. (The description given immediately below is an abridgement of the description given in their paper.) Hunt and Lansman also provide several illustrations of the use of the model to simulate results in the attention and performance literature. These results will be described briefly here.

The use of PASCAL for simulation is worth some comment in itself. LISP is a far more commonly used language, and has even been called THE language for computer simulation of complex mental processes. Our experience calls into question the almost unthinking acceptance of the necessity for relatively expensive LISP programming. The issue has been explored in more detail elsewhere (Hunt, 1983a). As the PASCAL-LISP controversy is peripheral to the main purpose of this project, the issue will not be developed further here.

Description of the Production-Activation Model.

A basic assumption of the model is that when a stimulus is presented two concurrent information processing sequences are initiated. One involves a pattern recognition process that culminates when a label identifying the stimulus is placed in working memory. The label provides an interpretation of the stimulus that can serve as a trigger for further actions. This sequence of pattern recognitions, actions, and further pattern recognitions will be called the "controlled" information processing sequence. In addition, stimulus presentation is assumed to initate an "automatic" processing sequence that behaves in quite a different way. Instead of relying on pattern recognition guided by information in working memory, the automatic processing sequence relies upon the spread of activation levels from one engram in memory to associates of that engram, without involving the working memory system.

The controlled processing system

Controlled processing can be envisaged as the

operation of a production system interpreter (Newell, 1973). Such interpreters contain two parts: a set of productions (pattern-action pairs) stored in long term memory, and a blackboard area that contains information about the current situation. At each cycle the pattern parts of all productions are compared to information on the blackboard. If any patterns are recognized, one or more of the associated actions are taken. Figure 1 shows the relationships between the blackboard and long-term memory utilized in the Production Activation Model. The blackboard itself is divided into three areas: two sets of external channels (one visual and one auditory) that contain information presented to the system, and a working memory area that contains information that the system itself generates as it interprets problem solving situations.

Figure 1 here

The static architecture implied by Figure 1 supports a dynamic information flow. Information is placed in the external channels by the "environment," i.e., by a process outside the scope of the model itself. The information

presented may be in either an "auditory" or a "visual" code. These names have been chosen for their obvious analogy to sensory modalities, but computationally the only distinction between them is that the stimuli are described in different codes. Information in the external channels is examined by the productions available in long-term memory. When an auditory or visual pattern is recognized, an internal label for the stimulus is placed in the working memory area. The internal label may either be in the (auditory or visual) sensory code in which the stimulus was presented, or it may be in an internal "semantic" code. If the label is in a sensory code, it is placed in either the "auditory" or "visual" channel of the working memory area. These channels provide a way for the system to respond to internally generated stimuli, represented as sensory codes. The internal channels are thus analagous to Baddeley's (1976) concept of auditory and visual buffers in working memory.

If the internal label is in the semantic code, it may be placed in any of the the several semantic channels in the working memory area. Baddeley and others have stressed the need for a modality free representation of information in working memory. The semantic code provides

such a representation.

The productions in long-term memory continually are matched against both the external and working memory channels. Thus configurations of working memory may themselves serve as stimuli for further actions. For example, suppose that two stimuli were placed on separate external visual channels. The model could be "programmed" (i.e., provided with an appropriate production system) that would select one of them, place it in the visual channel of working memory, and then use the internal visual code as a stimulus to place a semantic intepretations of the original stimulus in the semantic working memory area.

The following example, which is based on an actual simulation study, illustrates the process in more detail. Consider a two-choice reaction time study in which either of two visual stimuli - Stimulus 1 or Stimulus 2 - can be presented. The subject's task is to identify the stimulus, by making Response 1 if Stimulus 1 has been presented and Response 2 if Stimulus 2 has been presented. A production system can be constructed using two pairs of rules:

1. If stimulus x (x =1,2) appears on a visual channel, place the signal "recognized stimulus x" in working memory. Two productions are required, one for each value of x.

2. If the signal "recognized stimulus x" is in working memory make response x.

The condition part of a rule (the "if" clause) will be referred to as the pattern of a production. The consequent part (the "then" clause) will be referred to as the action. In controlled processing, a sequence of productions is executed in an order that is determined by their level of activation. The first step in controlled processing is determination of the extent to which there is a match between the stimulus and each of the patterns in long-term memory. A complete model of how stimuli and patterns are matched would constitute a theory of perception, which is quite beyond the scope of our work. Instead of including such a theory, the model includes a pattern recognition process that is proposed as sufficiently descriptive of human perception for our purposes.

The stimulus is represented as an ordered list of features, drawn from a feature alphabet, or code, appropriate to that particular type of stimulus. Distinct similarity matrices are associated with auditory, visual, and semantic codes. The (ij)th entry of this matrix is a number, between zero and one, indicating the extent to which the ith value of a feature in that code resembles the jth value. For example, if the stimuli were figures of varying shape, the entry for (triangle, circle) would be near zero, and the entry for (circle, ellipse) would be near one. The diagonal (ii) entries of the feature matrix are always one, indicating that a stimulus feature most resembles itself.

The similarity matrix notation provides a flexible way of describing features, since it allows for the possibility of a confusion without requiring that all conceivable confusions be permitted. For instance, a stimulus similarity matrix could be constructed to permit confusion between colors (e.g., red and orange) or forms (triangle and square) but never between colors and forms. Psychologically it would be more realistic to think of sub-dictionaries (and confusion matrices) within a large

dictionary of visual or acoustic features. In practice, it is easier to maintain a single dictionary for each type of sensory code.

Patterns are defined by ordered lists of pairs, (f,w), where f is a feature in the appropriate code and w is an indicator of the importance of the feature to the pattern. The value of w may vary from -1 to +1, depending on whether the feature is contraindicated, irrelevant (w=0) or mandatory. The resemblance of a stimulus to a pattern is computed using Luce's (1956) choice rule,

$$(1) \quad \text{Resemblance of stimulus to pattern} = \frac{\sum_{j=1}^{k} w(j)\ \text{sim}(s(j),p(j))}{\sum_{j=1}^{k} w(j)}$$

In this equation, k is the number of features in the stimulus and the pattern, s(j) is the jth feature of the stimulus, p(j) is the jth feature in the pattern, sim(s(j),p(j)) is the similarity of feature s(j) to feature p(j), as specified by the similarity matrix,

and w(j) is the weight of the jth feature in the pattern. The possibility that a stimulus may not contain all the features of a pattern (or vice versa) can be handled by including a null code within each code dictionary. The null code must not resemble any other code, i.e., the off-diagonal entries for the null row of the similarity matrix must be zero.

In some experiments patterns must differentiate between the appearance of a stimulus on an expected or an unexpected channel. This distinction is particularly important in studies of divided attention, where a person may be told to react to the presence of a signal in the right but not the left ear, or to a signal in the right but not the left of the visual field. To allow for this possibility, a pattern is further defined to have an additional "feature," corresponding to the channel on which the stimulus is expected. The importance of stimulus location is specified by stating a channel weight, c, varying from 0 to 1, where c=0 indicates that the channel is irrelevant, and c=1 indicates that the pattern is defined exclusively for one channel. The strength of a match between a stimulus and a pattern is then computed by the rule

(2) Match between stimulus and pattern = { resemblance if the stimulus is on the expected channel; (1-c)(resemblance) if the stimulus is on an unanticipated channel.

The distinction between channels and features deserves comment. Computationally, a channel is an array variable that takes as its value a vector of features. The pattern part of each production is similarly a vector of features, and "perception" is the process of comparing the value of a channel to the pattern part of a production. This establishes a hierarchy of dimensions of variation for stimuli. Stimuli may differ in their features, and differ in the channel on which they appear. The distinction is computationally important in the model, because patterns are first matched to stimuli by computing a weighted sum of matches based on corresponding features, and the resulting value then multiplied by a weight

determined by the channel. An alternative scheme would be to treat a channel as an additional feature of the stimulus. Consider visual figures that varied in shape, size, and color. Shape and size are determined by contour and color is not. Should color be considered as a feature to be added in with shape and size, or should a simulation be able to treat color in a completely different manner; i.e. as a channel? We have chosen the alternative of distinguishing between channels and features. The implications of the other alternative have not been studied.

No claim is made that the similarity computation rule is a theory of perception. (It would be of interest to replace the rule with a psychologically more justifiable one.) Using the similarity computation rule allows us to proceed with the task of studying the post recognition phenomena simulated by the Production Activation Model itself. This point is developed in more detail in the general discussion section.

The stimulus complex may contain information that matches several patterns to varying degrees. Therefore a "conflict resolution rule" is required to determine

which production is to have its associated action executed. Conflict resolution is a general characteristic of production systems (McDermott and Forgy, 1978). In the Production Activation Model, the pattern part of each production has associated with it a non-negative real number, a, called its activation level. One, but only one, of the factors involved in determining an activation level is the extent to which the pattern matches some part of the stimulus complex. The other factors are explained below. The important point here is that the conflict resolution rule is a procedure for comparing activation levels.

As a computational device, the program's state is computed for finite steps of time, called cycles. All computations within a cycle take place functionally in parallel. Within a cycle, at most one semantic, visual, or acoustic pattern may be selected for execuation. Therefore, patterns within a single modality (or code) are compared with one another to determine which one, if any will be selected. The conditions for selection are

1. The pattern's activation level must be above a preset threshold that is a characteristic of the pattern,

and

2. The activation level of the selected production must exceed the activation level of any other pattern stated in the same code by an amount, DELTA, that is a parameter of the system.

The fact that the controlled system can respond to at most one semantic, one visual, and one acoustic pattern within a single cycle will be referred to as the "bottleneck condition." The points at which productions compete for action selection will be referred to as bottleneck points. The Production Activation Model contains three bottleneck points, one associated with each of the codes.

A strong restriction of the model is that patterns are stated in terms of the features on a single channel. Thus it is not possible to define a pattern in terms of concurrent features on two channels, i.e., in terms of a multimodal stimulus complex. It is possible for the system to react to multi-channel, multi-coded stimulus complexes by recoding the components of these complexes to internal stimuli in the semantic code, and then reacting

to the constructed semantic stimulus. The point is that intervention by the controlled system is always required to construct such an internal system. There is no way that the system can react to multi-channel stimuli within a single time cycle.

Any production system could be realized within the controlled processing framework of this model. Since unrestricted computing systems are equivalent to Turing machines, it is generally held that they provide too much power to be realistic psychological simulations. The usual way to avoid the problem is to introduce the restriction that patterns must not exceed a fixed length, k^*, that could be looked upon as a limit on the capacity of working memory. There are then only a finite number of possible productions, corresponding to the finite number of possibly discriminable stimuli, given that each stimulus must consist of not more than k^* elements from a finite code.

There is another restriction, not stateable in the terminology of Turing machines but stateable by reference to the Production Activation Model, that may be far more important in limiting human capacity. It is the concept of

interruptability. Furthermore, this restriction interacts with limitations in the size of working memory. Imagine that the Production Activation Model, or some similar device, contains a production system that is logically sufficient to do an arbitrarily chosen calculation after a minimum of n steps ($n > 0$). Suppose further that there is some probability, q, that any arbitrarily chosen step may fail to execute because of an interruption. That is, the device is thought of as being embedded in an environment in which high priority stimuli for productions outside of the set in question appeared randomly on an external channel. If such a signal appears, its processing takes priority over the computaton currently being done. Let P(n) be the probability of completing an n step computation. Then

$$P(n) = (1-q)^{n} \qquad (3)$$

which becomes arbitrarily close to zero as n increases. Finally, suppose that the size of a production pattern is limited. The effect of this limitation would be to force a large computation to be broken down into several steps, thus increasing n. Clearly the computing power of the model is limited by the size of the patterns that it can recognize, and that limitation is exacerbated by the fact

that the system is interruptible by "irrelevant" stimuli.

The Automatic Processing System

The automatic processing system operates in a quite different manner than the controlled system. It is best understood by conceptualizing each production as a node in a network that is similar to the semantic networks described by Collins and Loftus (1975) and Anderson (1976,1983, a,b). The connection between any two productions, i and j, is stated as an association value, a(i,j), that takes some value between 1 and -1. If production i has activation level x(i,t) at time t, the activation level of production j will be increased by the amount a(i,j) * x(i,t) at time t+1. Thus information is passed from production to production by spreading activation, avoiding bottleneck points. All productions transmit information about their activation level simultaneously. A single production may send and receive activation from several productions, including itself. If the association link between two productions is negative (a(i,j) < 0) the sending production is said to inhibit the receiving production.

The two choice reaction time example can be extended to illustrate the automatic information processing system. Here it is useful to think of Stimuli 1 and 2 as associated with Responses 1 and 2 as a result of instructions, training and/or stimulus-response compatibility. For instance, suppose that Stimulus 1 is a right arrow ("->") and Stimulus 2 a left arrow ("<-"), and that Responses 1 and 2 consist of the movement of a lever to the right or left, respectively. Figure 2 shows the network of associations that would be used to simulate this situation. Three principles were used in constructing the network (1). They are

1. All productions activate themselves, positively. That is, $0 < a(i,i) < 1$ for all i.

2. Any production whose action might produce the precondition for a subsequent production is positively associated with the subsequent production. Thus the production recognizing Stimulus 1 primes the production that would recognize the associated semantic signal. (To illustrate, $a(v1,s1) > 0$ in Figure 2.)

3. If the pattern parts of two productions represent

logically exclusive interpretations of the stimulus, then the two productions inhibit each other. For this reason, $a(v1,v2) < 0$ and $a(v2,v1) < 0$ in the figure.

These rules were chosen because they have been found useful in a number of studies of self organizing systems. Note that Rule 3 is a logical analog to lateral inhibition, a phenomenon widely observed in the nervous system. The rules have been applied to the construction of semantic networks in all our simulation studies. In addition, only one value each is permitted for all self associations ($a(i,i)$), all positive associations, and all negative associations. The same values were used in all the studies reported here. The fact that reasonable results could be obtained without recalculation of parameters indicates that the model is robust.

Figure 2 here

Decay, Noise, and Refractoriness

If the automatic system operated exactly as

described, activation would spread through the system without limit. To avoid this, a decay mechanism has been introduced. At the end of each time cycle, all activation levels are reduced by a fixed fraction d ($0 < d < 1$). (In all of our work, d has been set to .5) In addition, biological information processing systems are assumed to be subject to minor perturbations. These perturbations are modeled by adding a randomly distributed noise element to each production's activation level during each cycle. The noise element is distributed normally with expectation of zero and a standard deviation, e. The e parameter is thought of as a fixed characteristic of an individual at a given point in time. Except where noted, a constant value of e was used in all simulations. Similar decay and noise processes are required in virtually every associative network model of learning and cognition.

In production executing systems, the activation level of a production must be reduced once its action is taken. Otherwise the system will keep repeating its selection of the same production until new input is received (McDermott and Forgy, 1978). In order to avoid this undesireable outcome, a refractory process has been introduced.

When a production is selected for activation its

threshold is reset to a value halfway between its original threshold and its current activation level. Subsequently, the threshold decays toward its original level at a rate determined by the decay parameter, d. This induces a refractory period, during which time new productions can be activated.

Simulation Studies

Simulations of a number of different experimental results have been conducted. Each of the simulation studies follows the same basic design. Production system 'programs' were created to describe the "conscious" actions that a subject was carrying out. Loosely, each of these programs can be looked upon as a statement of the subject's understanding of the experimental task. The programs themselves were intentionally quite simple, as are the instructions to a subject in the typical "attention and performance" task. The production system used in the Choice Reaction Time simulation described above is a good example. (Hunt and Lansman (1984) present a detailed description of each program.) The production systems were augmented by a network of "semantic associates" that, in effect, constitute a model of

automated information processing in the task at hand. Every effort was made to keep these models simple and non-controversial. Again, the network presented in the choice reaction time example is a good illustration.

The various experimental results were then simulated. The simulations were constructed under several constraints. In constructing semantic networks the same rules for network construction illustrated in the CRT example (i.e. positive forward associations coupled with lateral inhibition) were used throughout. Only three parameters were used to construct the networks; values for self excitation, lateral inhibition, and forward association. The lateral association parameter was set at (-1) x the self excitation parameter, and the forward association parameter was 2/3 as large as the self excitation parameter. Unless otherwise noted, delta was set at 1.0, the decay parameter at .5, and the noise parameter at .3. Parameter invariance was maintained throughout all simulations in order to obtain a severe test of the model.

Three criteria were used to choose experimental paradigms to simulate. Each paradigm had to isolate

behavior that has been considered to be basic to human rapid decision making and attention allocation. There had to be an ample literature showing that the parameters manipulated in the experimental paradigm had a consistent, reliable effect on behavior. The final criterion was that the simulation had to produce its results by the interaction between the interaction between the paradigm-specific production system and the model-invariant architecture of the model. This criterion was used to insure that any results obtained could be regarded as tests of the basic ideas behind the model, rather than as tests of the production system used in a particuar study.

Hick's Law : Choice reaction time studies have produced a number of highly replicable phenomena, some of which have assumed the status of "laws" in psychology. One of these is "Hick's law." Consider a situation analagous to the illustrative example, except that any of one of n ($n \geq 2$) stimuli may appear on a given trial. If each of the n stimuli are equiprobable, average reaction time increases as a function of the logarithm of the number of possible stimuli. This finding is known as "Hick's Law."

An n-choice reaction time study was simulated by expanding the production systems and networks given in the example to allow for 2, 4, or 8 stimuli and responses. The results are shown in Figure 3, which plots the relation between number of choices (on a logarithmic scale) and the number of time cycles before a response.1

"Response" refers to the execution of a production whose action included an external reponse. Figure 3 also shows results of a study by Taylor (1982), using human subjects. Clearly the results with the simulation mimic the human results up to a ratio transformation (milliseconds per cycle).

Figure 3 here

Speed-accuracy tradeoffs . The relation between speed and accuracy of responding in choice situations has been the subject of considerable study. If a person speeds up his/her response in a particular choice situation the probability of an error increases. The relation between probability of correct response and time taken to respond is almost always a monotonically increasing, negatively

accelerated function (Pachella, 1974). On the other hand, changes in either the conditions of the task or the state of the individual that produce slower reaction times almost always also increase the frequency of errors. These two effects will be refered to as the negative and positive speed-accuracy relations.

Both the negative and the positive relations can be produced by the simulation, by manipulating different parameters. Figure 4 shows the effect of manipulating the DELTA parameter. Recall that this parameter determines the extent of dominance that a production must have over its competitors, before its associated action is taken. Loosely, at high values of DELTA conflict resolution takes longer, but is less likely to result from random fluctuations in production activation levels. Thus manipulating DELTA will produce a negative speed-accuracy relation.

Figure 5 shows two different ways of producing positive speed-accuracy relations. Figure 5A was produced by holding the DELTA parameter constant and varying the size of the noise parameter. Increasing the values of the noise parameter both slowed responding and decreased

accuracy. This can be thought of as being an analog of studies that compare responding across people of differing information procesing characteristics, e.g. people of markedly different ages. Figure 5B shows a positive speed-accuracy relation produced by holding the DELTA and noise parameters constant, and varying the parameter establishing the simlarity between the two visual stimuli. This is analogous to plotting data from an experiment in which the stimuli to be identified vary in distinctiveness.

Figures 4, 5 here

Stimulus repetition effects : In two choice CRT experiments response time is a function both of the choices available on the current trial and the relation between the current and the previous trials. There are two aspects to this relationship; the effect of the sequence of stimuli presented and the effect of the response-stimulus interval, i.e. the time beween the occurence of a response and the presentation of a new stimulus. The two variables interact to produce a rather

complex pattern of behavioral effects.

A repetition is defined to be the presentation of the same sequence on two or more successive trials. An alternation is defined to be the presentation of different stimuli on successive trials. While an alternation could be defined for experiments involving any number of stimuli, only the 2-choice experiment will be considered here. Thus if the stimuli are arbitrarily labeled A and B a repetitive sequence would be a sequences of repeated presentations, as in A..A..A..A, while alternation would be represented by the sequence A..B..A..B. An experiment by Kirby (1976) provides a good illustration of the basic phenomena. Responses to repetitive sequences were rapid at a response-stimulus interval (RSI) of 50 msecs, while responses to alternating sequences were rapid at an RSI of 2000 msec.

Kirby (and others) assumed that the repetition effects at short RSI's are due to involuntary, automated phenomena. The repetition effects observed at long RSIs are generally assumed to be due to the subject's having a somewhat conscious expectation that the stimulus sequence will be varied. This produces the gambler's fallacy, a

belief that an A stimulus is more likely to be followed by a B than by another A, and vice versa.

A production system model was developed to realize this reasoning. The production involved can be logically divided into two parts. One part contains the productions for choosing a response. These were identical to the productions used for the Choice Reaction Time experiments. In addition, productions were included that took as their stimulus the fact that a particular response had been made, and used that cue as a signal to generate a priming signal expecting a different stimulus. These productions were active during the RSI, while the first subset of productions were activated by a stimulus presentation.

Figure 6 demonstrates response and alternation effects at short response-stimulus intervals. Panel A shows the effects in data produced by the production-activation model. Sequence AAAA represents the repetitive presentation of the same stimulus on four successive trials, sequence ABAB represents presentation of alternating stimuli. In the runs that produced this data stimuli were presented immediately after the model had made a response. There is a strong repetition effect

and no alternation effect. Panel B of Figure 6 is a replotting of Kirby's (1976) data for his 50 msec RSI ondition. As in the model, there is a repetition effect but not an alternation effect.

Figure 7 presents similar data for long RSI's. Panel A shows the result of model runs that contained and introducing a blank period (i.e. no stimulus present) of six internal cycles between the response and the next stimulus presentation. During this period the model continued to redistribute activation, and to react to any internally generated stimuli in the manner described above. Panel B is a replotting of Kirby's data for the 2000 msec. RSI condition. In both the simulated and the human data, repetition effects do no appear, but alternation effects do.

In the human data, responses at the 2000 RSI condition were more rapid, overall, than responses in the 50 msec RSI condition. This is not true in the model. No attempt has been made to reproduce this effect, which may be due to properties of the motor system rather than to the interaction between expectation and stimulus identification.

Figures 6 and 7 here

Splitting attention. In choice reaction time studies the participant must identify a stimulus that appears in a known location. The next series of studies involve the detection of stimuli that appear randomly at different locations. An experiment by Kinchla (1980) provided the motivation for the simulation. Kinchla's observers had to attend to two small lights, at different locations in the visual field. In terms of the model, the two locations were treated as separate external visual channels. On each trial one or the other of the lights might flicker briefly. The observer's task was to indicate whether or not a flicker had occurred on either channel. Thus the dependent variable was the probability of a correct detection, rather than the latency of a response. The chief independent variable in the experiment was the priority that the observer was to assign to each channel. Priority was determined by instructions, and by points rewarded for a correct detection.

The simulation for this task was closely related to the CRT simulation. Information was presented over the two visual external channels. Initially both channels had null signals (S1) placed on them. These signals corresponded to the lights. Then, on experimental trials, a target (S2) signal was placed on one of the channels briefly. Catch trials were also included, in which no target signal was presented. (Naturally, Kinchla also used catch trials.) The target signal was then replaced with the S1 signal.

To permit false alarms, which do occur in this type of study, the resemblance between S1 and S2 stimuli was set at .50.

The notion of priming was used to simulate the effect of instructions, in a manner similar to that developed for the study of alternation effects. It was assumed that, given appropriate instructions, a person could generate an internal "priming" signal that would have the effect of lowering the response thresholds of all productions associated with a particuar channel. Thus the threshold value for each channel served as the primary dependent variable. Thresholds varied between 1 and 0,

complementarily. That is, if threshold x was assigned to the productions of channel 1, threshold 1-x was assigned to the productions of channel 2.

Data from this sort of study is usually represented as a "performance operating characteristic" (POC), in which the accuracy of detection of targets on one channel is plotted against the accuracy of detection of targets on the other channel. Figure 8 presents the POC obtained by the simulation. Kinchla's data is also shown for comparison. Clearly the human and the simulated data are tracing out the same function. Note that in Kinchla's study subjects never completely ignored the less relevant stimulus, so the POC obtained from human observers does not cover the extreme points that could be simulated.

Figure 8 Here

Stroop studies . The last simulation to be reported deals with the Stroop task, a situation considerably more complicated than the other paradigms described here. In Stroop situations signals are presented simultaneously on

two separate channels. The participant is instructed to make an identifying response to the stimulus on one channel, while ignoring the other. The two stimuli will be referred to as the relevant and irrelevant stimuli, respectively. There are three basic experimental conditions. In the neutral condition the relevant and irrelevant stimuli are not associated with either common or mutually exclusive responses. In the conflict condition the relevant and irrelevant stimuli have strong, and mutually contradictory, associations with the possible responses. In the facilitating condition the relevant and irrelevant stimuli are both highly overlearned cues for the same response.

In Stroop's experiment participants had to name the color of ink in which words were printed. The words were themselves color names; e.g. the word GREEN printed in red ink. This, obviously, is a conflict condition. In a facilitation condition GREEN would be printed in green ink, while in a neutral condition either a color patch or a non-color word (e.g. DOOR) would be presented in colored ink. In general, if people are asked to name the ink color there is a marked slowing of identification responses in the conflict condition, and a negligible

increase of speed in the facilitation condition (Dyer, 1973). Reading the word takes half as much time as color naming, and is relatively uninfluenced by ink color.

The production system developed to simulate the controlled part of responding in a Stroop experiment was a straightforward extension of the simulations used in the CRT and dual task studies. Productions were included for the recognition of visual form and color stimuli, the generation of an internal "auditory" code corresponding to the name of the visual stimulus that had been recognized, and finally productions for producing an external response based upon the recognition of an internal auditory code.

The simulation of automatic performance in the Stroop task was based on the model proposed by Morton (1969). Morton assumped that when a Stroop stimulus is presented the visual form stimulus activates prior associations with an auditory code, while visual color stimuli activate associations with semantic codes. Accordingly, the auditory and semantic codes activate each other. Since the required response in a Stroop study requires the generation of an auditory code, responding will be faster to the form of the word than to the color. In a Stroop

"conflict" trial (e.g. the word GREEN presented in red ink) the controlled and automated system are thus opposed to each other, resulting in a long reaction time as the controlled system generates sufficient internal stimuli to gain control over responding.

Figure 9 depicts the results of a simulation of the six possible Stroop conditions. Most of the Stroop findings are replicated. The color naming-conflict condition produces by far the slowest responding. Facilitation effects are relatively small for color naming, and non-existent for word naming. There are two exceptions to the normal Stroop finding. One is that the "word reading" conditions are not as much faster than "color naming" as they should be. The second contradiction to human data is that conflict is found in the word reading condition. That is, it takes longer for the simulation to "read" the word RED printed in green ink than it takes to read RED printed in a neutral color.

There is a simple way to eliminate these contradictions between human and simulated data. The Stroop phenomenon is unlike the other phenomena studied in that it relies on extra-laboratory learning, i.e. the

highly overlearned association between word forms and auditory codes. To simulate the effect of overlearning, we relax the rule that all parameters of the simulation are to remain invariant over all experiments. In particular, the value of the association between word forms and auditory codes was doubled (from .25 to .5) with all other parameters held constant. The results are shown in Figure 10. Form naming becomes faster than color naming, and the conflict in the word reading condition is reduced although not eliminated.

Empirical Studies

Several experimental studies were undertaken to complement the theoretical investigations reported in the previous section. These studies were intended either to provide data to guide in development of the theory or to provide data relevant to conflicts between the position taken in developing the Production Activation Model and the position taken by other theorists who have discussed the same phenomena.

One question was central to all the studies; "How is

attention controlled?" The Production Activation model takes the strong position that diversion of attention from one task to another is due to structural interference; i.e. to the requirement that at most one production within a given modality can have its action executed at any one time. This point of view leads to a further conclusion; the effeciency of production execution should be determined by the extent to which information can be handled quickly within a given modality, but could vary independently across modalities. Put another way, one could use the Production Activation model to design two distinct "robots", one that was very good at executing auditory productions but relatively ineffecient at executing visual productions, and another that was ineffecient at executing auditory but effecient at executing visual productions. This conclusion is somewhat at variance with the position taken by Gopher (1983), who has asserted that there is a generalized ability to control attention that is not limited to a particular stimulus mode. We shall examine this point further in a moment, but first we consider some points concerning training and effecient stimulus recognition.

According to the Production Activation model, the

most effecient execution of responses will occur when a stimulus-response sequence is completely encapsulated by one or more productions that are so tightly associated with each other that activation of the first production in the sequence is sufficient to activate all other sequences. In such a case the term "automated responding" is appropriate, since all information processing is done within the automatic processing system. This, of course, is a statement about the model. Behaviorally, automation is normally defined by a demonstration that response speed and accuracy is virtually independent of stimulus complexity (Schneider and Shiffrin, 1977). An assumption of the Production Activation model is that this independence can be achieved for any stimlus-response sequence that contains no choice points, regardless of modality. On the other hand, cross-modal automation is not seen as possible.

Automated responding has often been demonstrated within the visual modality (cf. the experiments and review by Schneider and Shiffrin, 1977). One of the first experimental studies done during this project demonstrated the same effects for audition. Poltrock, Lansman, and Hunt (1982) asked subjects to detect target words in a

dichotically presented stream of words. The number of targets (the "memory set") varied from two to four items. Presentation was either under constant mapping (CM) conditions, in which the same targets were used on each trial, or under varied mapping (VM) conditions, in which the targets varied from trial to trial. These conditions are directly analagous to the CM and VM conditions in visual scanning. Essentially the same effects were obtained in the auditory as in the visual scanning paradigms. After practice, the relation between performance and the number of targets scanned (or, for that matter, the number of items presented) remained constant in the VM condition, but was much reduced in the CM condition. This finding is of interest in general, because it extends the phenomenon of "automated target scanning" to audition. The study also provides justification for the use of an "amodal" mechanism for stimulus identification in our simulation studies.

The Poltrock et al. studies are important for their empirical findings; they extend the concept of automatized scanning to the visual modality. Theoretically, they can be looked upon as a justification for the simplest possible stimulus identification mechanism; one that does

not vary with stimulus modality. Tests of complications in the model are of somewhat more interest. One of these has to do with mechanisms that establish stimulus sensitivity. It is well known that in certain situations people can be "set" to recognize particular stimuli. Two empirical procedures may be used to establish a set. One is frequency. Other things being equal, stimuli that are encountered frequently will be identified quickly. The other mechanism is an explicit warning. If a stimulus is preceeded by a warning signal that indicates that a stimulus will probably appear, then the stimulus will be reacted to quickly if it does appear.

The Production Activation Model ascribes the two ways of establishing an expectation to two fundamentally different mechanisms. Frequency is seen as establishing a high "resting" level of activation or,equivalently, a low threshold. Thus only a small input from the environment is needed to trigger the productions required for stimulus identification. This explantion derives frequency effects from properties of the automatic processing system. Expectancies established by signals are modeled by the firing of productions that recognize the warning signal, and use it to maintain a priming signal in working memory.

(See, for instance, the explanation of alternation effects in the simulation of choice reaction time studies.) In the theory, expectancies associated with warning signals are produced by the controlled processing system.

Lansman, Farr, and Hunt (1984) present an experiment that offers support for this position. One of the definitions of automatic processing is that it is not disrupted by concurrent tasks. By contrast, controlled processing can be defined by its susceptibility to interference by a concurrent task. Lansman et al. had subjects respond either to auditory or visual probe signals. The signals were either presented alone or as probe signals during a concurrent memory task. In their first experiment Lansman et al. varied the frequency of auditory or visual probes. Frequency had the expected effect on reaction time, resonses were faster to more frequent signals. Furthermore, and central to the present discussion, the magnitude of the frequency effects were identical both in the "probe alone" condition and when the probe was done concurrently with a memory task. Thus frequency appeared to be acting through the automatic processing system because it was not disrupted by a concurrent task. In a second experiment auditory and

visual probes were presented with equal frequency. Prior to each trial, however, a warning signal indicated whether or not a visual or an auditory probe would appear. The signal was correct 80% of the time. When the subjects' only task was to respond to the probe, responses were faster when the expected (auditory or visual) probe did occur. When the probe task was done in conjunction with the visual memory tasks the effect of signal accuracy was greatly reduced for auditory probes, and eliminated for visual probes. The fact that the effect of the warning signal was disrupted by a concurrent task is an indication that the effect was produced by controlled processing.

The final experimental study to be reported deals with a question about individual differences. There has been considerable speculation about the existence of a reliable trait for the ability to control attention. When Kahneman (1973) presented his well known proposal that attention be regarded as a power source, analagous to electrical power, he suggested that the amount of attentional resources available might vary as a function of the (temporary or permanent) health status of the individual. Kahneman's ideas lead naturally to the suggestion that the amount of attentional resources

available might be a characteristic of the individual. Several experimental studies seemed to offer support for this ideas. Perhaps the best known of these was a series of experiments by Gopher and his collaborators (reviewed in Gopher, 1983), which demonstrated correlations of about .3 between performance on a task that required rapid shifting of attention from one ear to another and performance on a variety of "real world" tasks, including automobile driving and flying. Related evidence has been presented by Stankov (1983), in a series of studies that use a more conventional psychometric approach than Gopher's work. Stankov isolated a factor whose highest loadings were on tests that required simultaneous execution of two auditory tasks. It would be consistent with Kahneman's model to assume that such tasks push people close to the limit of their attentional resources. Some of our own earlier studies of visual primary tasks lead to a similar interpretation (Lansman and Hunt, 1982). In fact, we had published a mathematical model that gave a rather good account of the data from visual dual tasks by postulating a characteristic level of individual attentional resources (Hunt and Lansman, 1982).

There are two problems with the above studies. Each

of the studies was interpreted as evidence for a general ability either to "have attentional resources" or to "allocate attention effeciently." However, each of the studies relied entirely on auditory or visual material. It is possible that there are actually separate attentional factors; one for each stimulus modality. (In fact, Wickens (1979) has presented evidence for this proposition.) The second problem was that strong theoretical attacks have been made on the concept of attention as a resource. Allport (1980) presents a good review of the issue. In fact, the Production Activation Model that has been developed here does not contain any concept akin to generalized attentional resources. In the model dual task interference is produced solely by competition for resources within each stimulus modality (including the internal "semantic" modality).

We have conducted a study that we believe offers strong evidence against the concept of a single "attentional resource" trait (Lansman, Poltrock, and Hunt, 1983). We asked subjects to perform three separate attention demanding tasks. In the single task conditions they monitored a stream of stimuli, signalling when they had detected pre-established targets. (This is a

conventional scanning task.) In the dual task condition subjects had to scan for the presence of targets in two simultaneously presented streams of signals. In the split attention task subjects had to examine one stream of signals while ignoring another, simultaneously presented stream. Finally, all three tasks were presented in both the auditory and visual modalities.

Various models of individual differences in attention were fit to this data, using the confirmatory factor analysis technique. The model that best fit the data contained two attentional resource factors; one for the auditory and one for the visual modality. The two factors were reasonably highly correlated (r = .61), but a single factor model (i.e. r = 1.0) most definitely did not fit the data.

Because of the comprehensiveness of the tests used, and because of the sensitivity of the statistical technique, we regard this study as strong evidence against the proposal that there is a single attentional factor. We do point out, though, that the high correlation between mode-specific factors could easily lead to the misidentification of a single factor in a statistically

less powerful analysis. Also, in hindsight, it is unfortunate that we did not include Gopher's attention switching task in our measurement battery. At present the literature supporting this task as a measure of (auditory or general?) attention is stronger than the literature supporting any other single task. In future work we hope to develop a visual analog of Gopher's auditory task, and to study the pattern of correlations between the two attention switching tasks, and between them and other tasks said to require generalized attentional resources.

Integrative Reports

General theories such as the Production Activation Model can be used in three ways. Two have already been illustrated; the simulation of specific experimental results and the use of the theory to generate questions for new empirical research. The third use of a general theory is to order one's thinking about very large topics. Occasionally this use of a theory is called a "world view", to contrast with specific studies. World view approaches are not capable of disproof; they are accepted or rejected because people do or do not find them convenient. The utility of a theory as a world view is

best argued by illustration. Three such demonstrations have been attempted.

Individual differences in cognition . The concept of thinking as production activation has been used to order a review of our knowledge about individual differences in cognition (Hunt, 1983b). Three types of intellectual functions were identified; functions that are sensitive to the basic parameters of a production system machine as a machine, functions that are sensitive to the presence of content-free productions for solving problems in general, and functions that depend upon the existence of content-specific problem solving methods. A selective review was made of recent studies on individual differences in human information processing, using this trichotomy. This paper can be looked upon as a further contribution to the perrenial discussion of "what is intelligence." It is unlikely that the last word has been said on this topic.

A revised version of the paper has been prepared as a non-technical presentation for Department of Defense personnel managers (Hunt, 1984a).

The analysis of individual differences has been extended to a consideration of new forms of intelligence testing. Hunt (1982) pointed out that the considerable amount of research on individual differences over the past ten years provides strong evidence for a need to expand our definition of intelligence. Furthermore, the advent of inexpensive microcomputer technology makes it feasible to use a flexible, individually tailored testing procedure. The term "tailored testing" has been intentionally introduced, in order to contrast it with another, commoner, use of the term.

Tailored testing is generally understood to mean a procedure in which the items are chosen to be maximally discriminative at the ability of the individual being tested. This is done by using interactive (computer controlled) algorithms for item selection. The computer program's responses are guided by the latent trait model of test taking. Tailored testing in this sense is already being used in a number of practical situations, and most notably in the redesign of the Armed Services Vocational Aptitude Battery (Green et al., 1982). Tailored testing in this sense deals with the evaluation of abstract abilities, without any concern for a psychological theory

of the abilities to be evaluated.

Hunt (1982) presented a case for another sense of "tailored testing", in which the concept of the tests to be given is chosen from a broad range of tests that define many different cognitive abilities. He proposed that instead of a "battery" of tests to be given to everyone, tailored testing should use an "armory" of tests that would be given, selectively, to different people depending both upon their test scores and the purpose of the testing. His argument was based on two assumptions. The first was that we should very considerably expand our idea of intelligence beyond a definition based on functions evaluated in extant tests. The second assumption was that the new technology of computer testing expands the sort of functions that can be tested.

The latter assumption was explored in more detail in a report by Hunt and Pellegrino (1984). After reviewing the dimensions of intelligence that are tested by conventional methods, they identified psychological functions that were either extensions of presently tested dimension, or new dimensions, that could only be tested by the use of interactive computing, accompanied by reaction

time measures and by the use of dynamic stimulus displays. Hunt and Pellegrino concluded that tests of visual-spatial ability and of the ability to control attention could be considerably expanded upon by the use of computing technology. Tests of inductive and deductive problem solving ability seemed to be less likely to be changed by the technology. Conventional means seem quite adequate to evaluate verbal ability, as would be done for personnel evaluation. However diagnostic testing to gain a qualitative picture of a particular individual's verbal skills could be expanded using computer controlled testing methods.

Verbal comprehension : The ability to comprehend verbal messages is an essential part of human reasoning. Furthermore, this is very much a real time task. Listeners have to keep up with speakers, and readers can't read too slowly or they won't get through their in-boxes. Therefore a theoretical model that is intended to apply to a variety of situations must have something to say about verbal comprehension.

Hunt (1984b) has presented a theoretical analysis of

verbal comprehension as a problem in attention allocation. The paper identifies three classes of information processing during verbal comprehension; the lexical analysis of individual words, syntactical-semantic analyses of the information contained in texts, and pragmatic analyses of text information in the context that it is received. Of course, such a trichotomy is not new. The contribution of the analysis was a consideration of the attentional demands of each of these tasks. It was pointed out that only lexical analysis can become "automated", since it is the only aspect of verbal comprehension that satisfies the constant-mapping requirement for automation. Syntactical and semantic analysis, by their nature, require the rearrangement of information in working memory. A similar remark can be made about integrating contextual information into one's representation of a linguistic message. In fact, as the report points out, it would be better to regard the representation of the linguistic message as just one source of information as one builds a general representation of what is going on.

From the viewpoint of an attention theorist, the interesting thing about verbal comprehension is that it

presents the comprehender with a dual task. Information being received must be analyzed at the lexical and syntactical-semantic levels as its meaning is being incorporated into a representation of the message in context. The lexical, syntactical-semantic, and pragmatic processes can be ordered from least to most, in terms of the attentional effort that they require, because of the amount of automation possible in each task. On the other hand, the lexical task must be assigned the highest priority, followed by the syntactical-semantic and pragmatic tasks, because of the time considerations involved. The paper explores the interference patterns inherent in comprehension, suggests how the attention allocation task is normally resolved, and indicates points at which the process may break down.

The Evaluation of Memory : The clinical assessment of memory is an important aspect of the diagnosis of an individuas mental capacity. The problem is particularly important in situations involving aging (e.g. Alzheimer's syndrome), but it also occurs, at much younger ages, in cases involving brain injury, some forms of meningitis,

and uncontrolled alcoholism.

In response to an invitation to address the Talland Memorial Conference on Aging, Hunt (1984b) used the Production Activatin Model as a theoretical framework for the memory assessment problem. Particular attention was paid to the difference between "echoic memory" for exactly the stimuli presented, as is tested in memory span tests, memory for a general representation of what is going on, as is required in the working memory area of the simulation, and the long term memory contained in the production memory. The paper also considers the tradeoffs that are possible between effeciencies in production memory, which would be established by learning, and effeciencies or ineffeciencies in the mechanical aspects of conflict resolution and production activation. The ideas in the model were used to address a number of practical issues concerning the evaluation of an individual's memory in different situatons.

Concluding Remarks

The goal of this research project was to develop a comprehensive model covering situations in which performance is limited by attention allocation and in situations in which performance is limited by reasoning and problem solving. A simulation technique already well explored in the problem solving area was adapted to cover the attention and performance area. Results from a number of representative attention and performance paradigms have been simulated satisfactorily. This establishes the breadth of the model.

Further demonstrations of the breadth of the model were shown by its use as an integrative device. It was used to order the literature in several fields. The greatest attention has been given to the use of the model to bring some order to a number of wide-ranging studies of individual differences in cognition. The theoretical analyses have suggested some new ways of testing an individuas mental capacity. These are now being explored.

Perhaps the most interesting of these questions concerns the measurement of an individual's ability to

allocate attention to different aspects of a task. In particular, we would like to see some resolution of the questions raised by the contrast of our own work on the measurement of attention with the work of Gopher and his colleagues. Is attentional control a trait that is specific to a stimulus modality, or is it a more general trait? If it is a more general trait, what are the best ways of measuring it? These questions are related to our more general interest in developing new methods of measuring human information processing ability. They will be pursued in future work.

There are two theoretical issues that ought to be explored further. The work cited here has shown that the Production Activation Model can cover the field of attention and performance in breadth. Can it cover individual microtopics in depth? This is a crucial question for scientists interested in the fine details of modeling. Can the Production Activation model be specialized to mimic the nuances of changes within a particular experimental paradigm? This issue is now being explored in two studies. One deals with different varieties of the Stroop paradigm, the other deals with changes in repetition effects as subjects learn to

recognize repetitive stimulus patterns.

Specializing a model is the way that one demonstrates the worth of a theory as a guide in pure research. If a theory is to be a guide in applied research, it must be shown to generalize to very complex situations. An attempt will be made to do this over the next few years. We are now conducting research on the modeling of performance in much more complicated "dual task" situations. These tasks can be characterized as combining visual, verbal, and psycho-motor subtasks. An example is the combination of tracking tasks with arithmetic and/or verbal reasoning tasks. The Production Activation Model will be used to order the data from these very complex situations. The success of this simulation should provide an evaluation of the use of the model as a guide for human engineering studies.

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Figure Captions

Figure 1. A schematic of the architecture of the production-activation model.

Figure 2. The semantic network used to connect productions in simulating a two-choice reaction time study. V[x] is the rule "if visual stimulus x is recognized, create semantic stimulus S[x]." S[x] is the rule "if semantic stimulus x is present make response s."

Figure 3. A simulation of Hick's law. Reaction time increases logarithmically with the number of alternatives in the model. Human data from Taylor's (1982) study shows a similar relation.

Figure 4. Reaction time and accuracy are both increased by increasing the DELTA paramenter. This mimics the negative speed-accuracy relation.

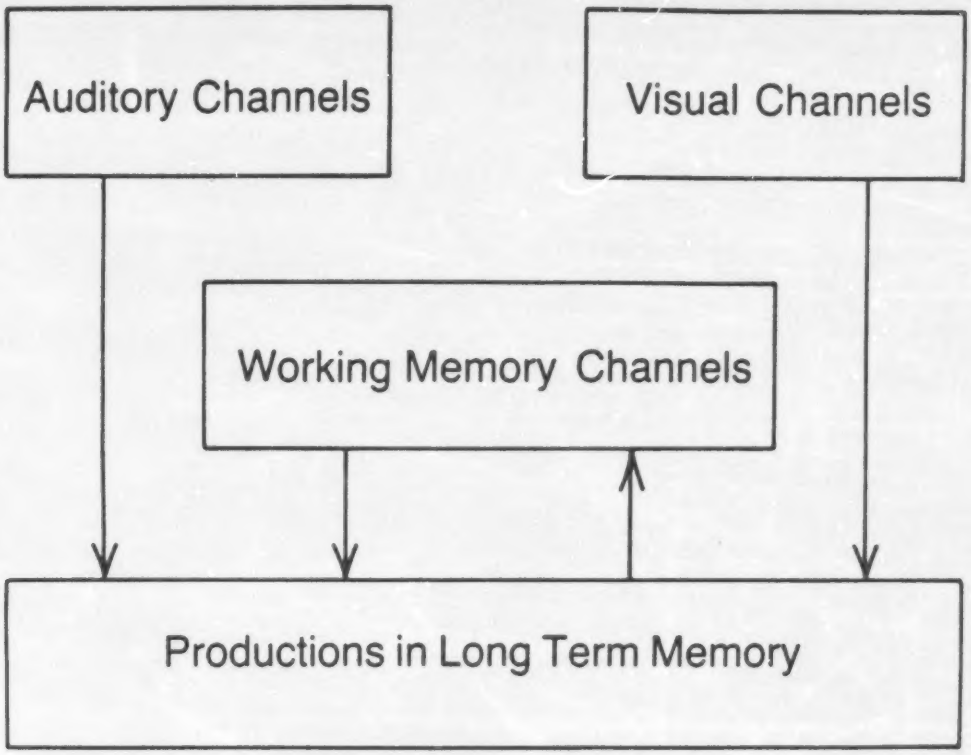
Figure 5. Reaction time increases and accuracy decreases if noise is added to the system internally (Figure 5a) or if the similarity between stimuli is increased (Figure 5b).

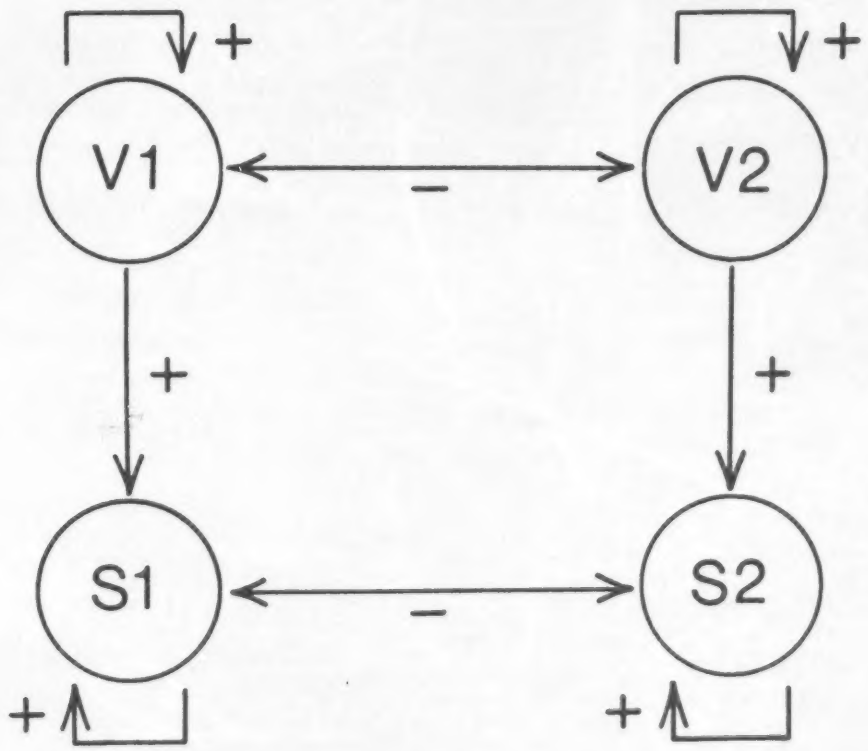
Figure 6. Responding to repetitive stimuli (AAAA) of alternating sequences (ABAB) as a function of the position of the sitimulus in a sequence. Panel A shows data from the model. Panel B shows data from Kirby's (1976) study. Data is shown for short RSI conditions.

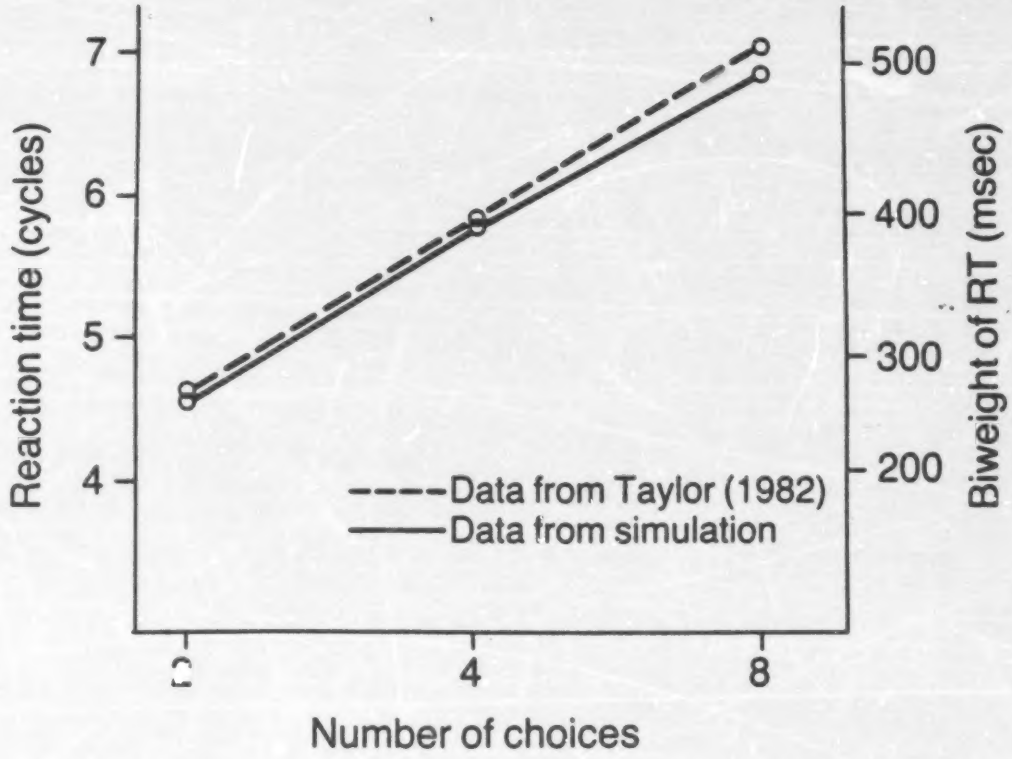
Figure 7. Responding to repetitive stimuli (AAAA) or alternating sequences (ABAB) as a function of the position of the stimulus in a sequence. Panel A shows data from the model. Panel B shows data from Kirby's (1976) study. Data is shown for long RSI conditions.

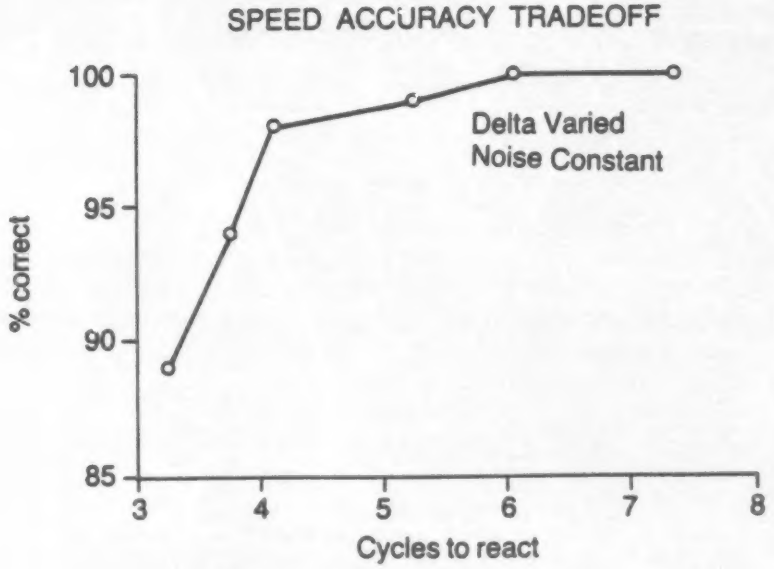
Figure 8. The performance operating characteristic for monitoring two channels. Squares are data produced by the model. Triangles are data replotted from Kinchla's (1980) study.

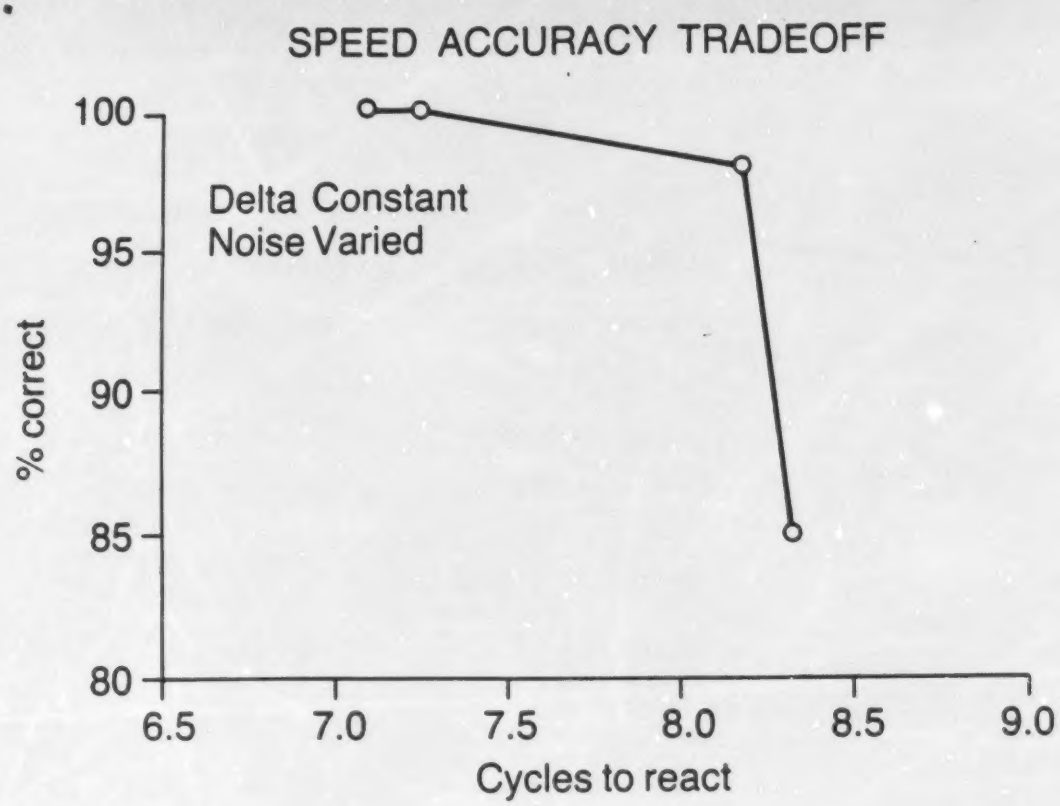
Figure 9. Time to react as a function of conditions in standard stroop paradigm.

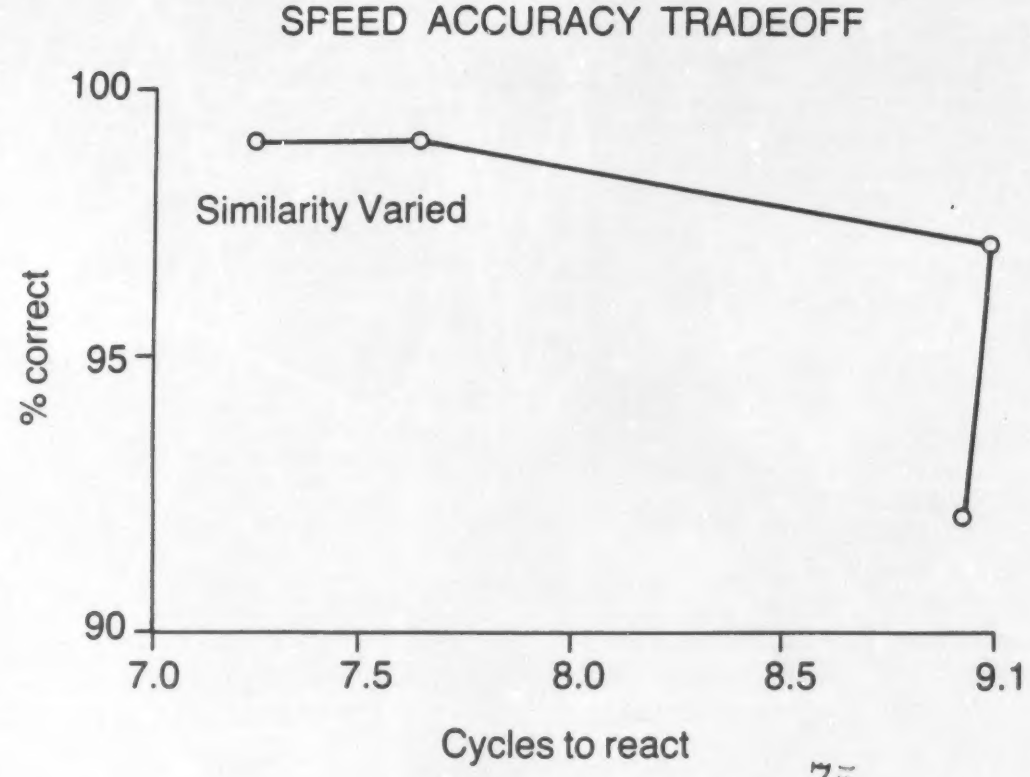

Auditory Channels
Visual Channels
Working Memory Channels
Productions in Long Term Memory

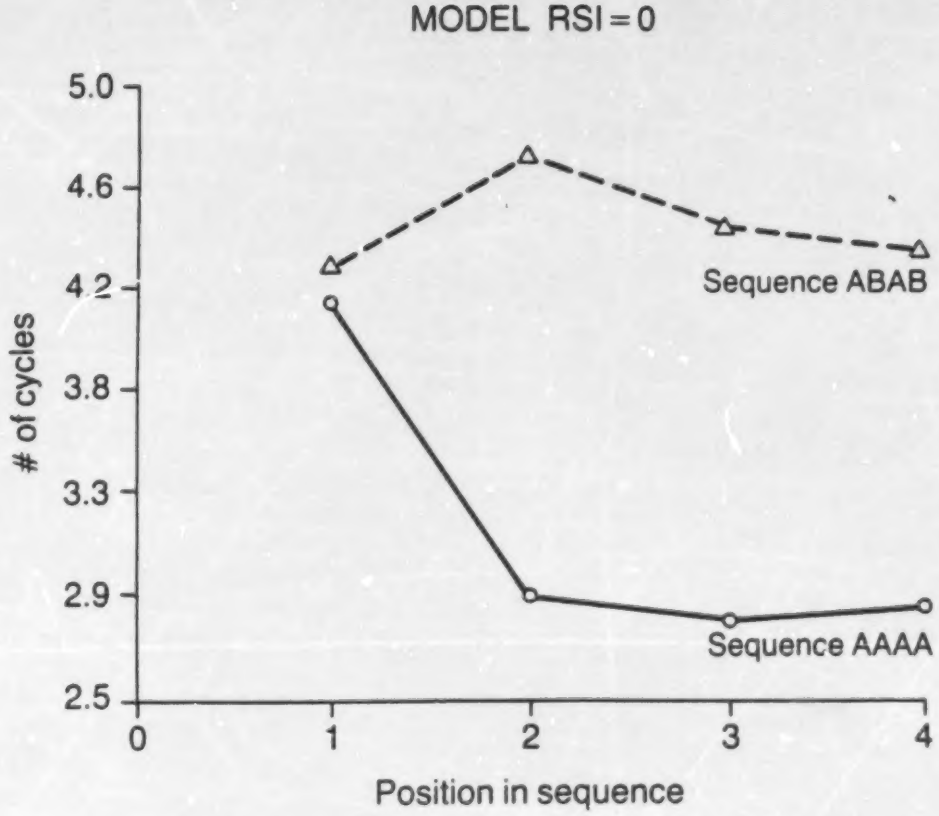

+
+
V1
V2
–
+
+
S1
S2
–
+
+

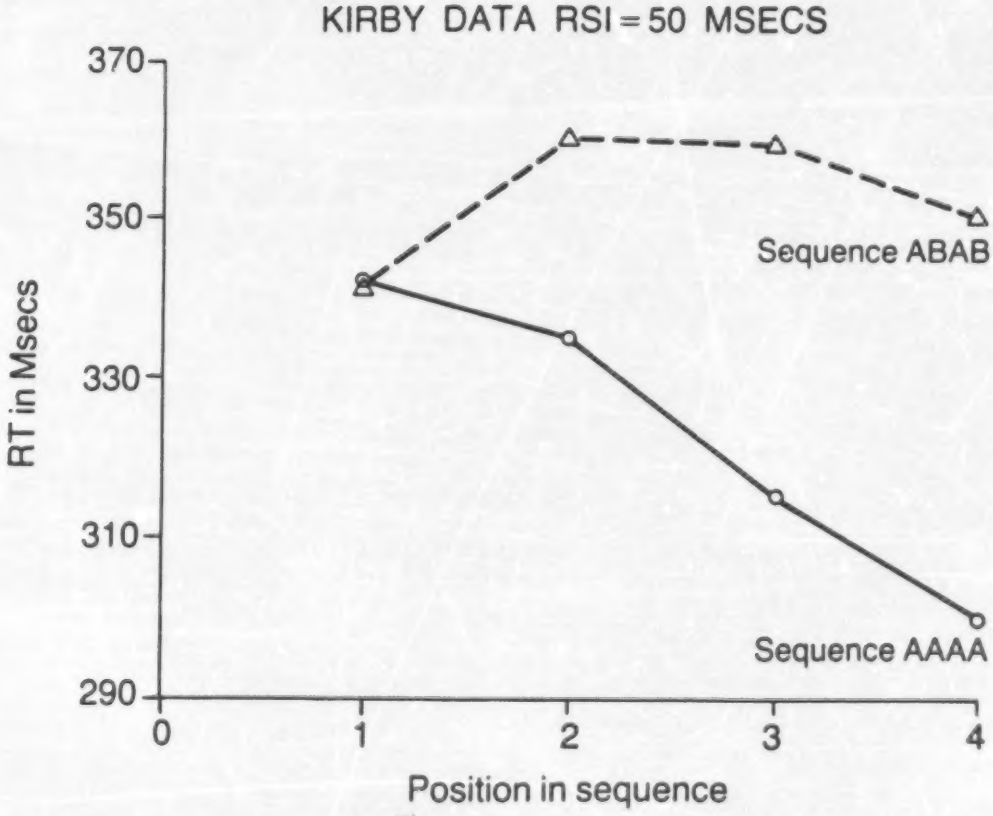

Reaction time (cycles)
7
6
5
4
500
400
300
200
Biweight of RT (msec)
Data from Taylor (1982)
Data from simulation
4
8
Number of choices


SPEED ACCURACY TRADEOFF
100
95
90
85
% correct
Delta Varied
Noise Constant
3
4
5
6
7
8
Cycles to react

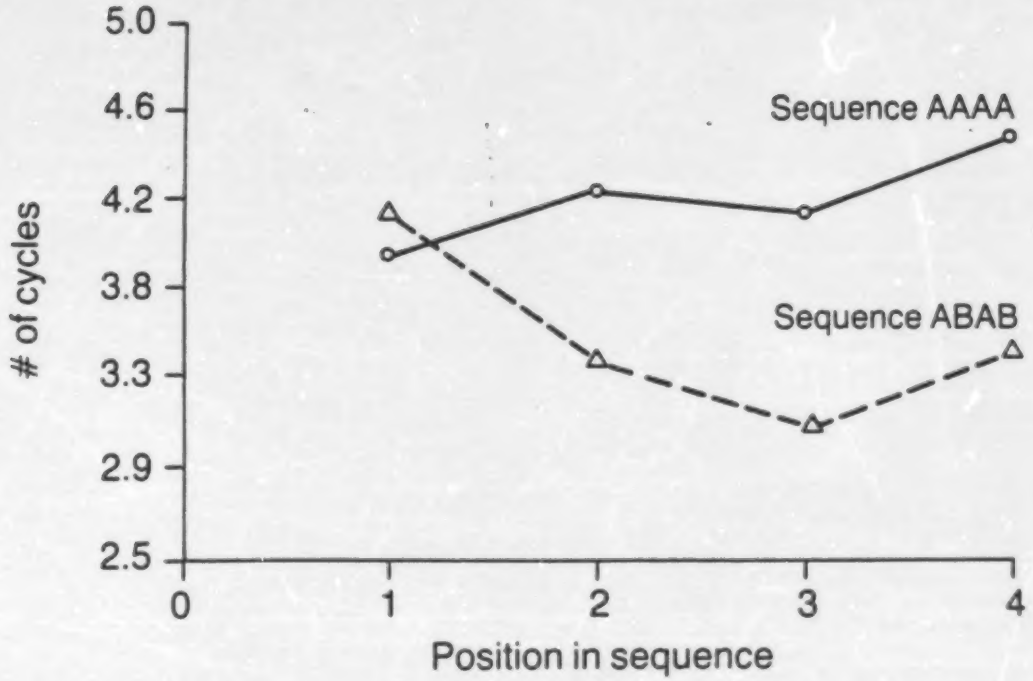

SPEED ACCURACY TRADEOFF
100
95
90
85
80
% correct
Delta Constant
Noise Varied
6.5
7.0
7.5
8.0
8.5
9.0
Cycles to react


SPEED ACCURACY TRADEOFF
100
95
90
% correct
Similarity Varied
7.0
7.5
8.0
8.5
9.1
Cycles to react

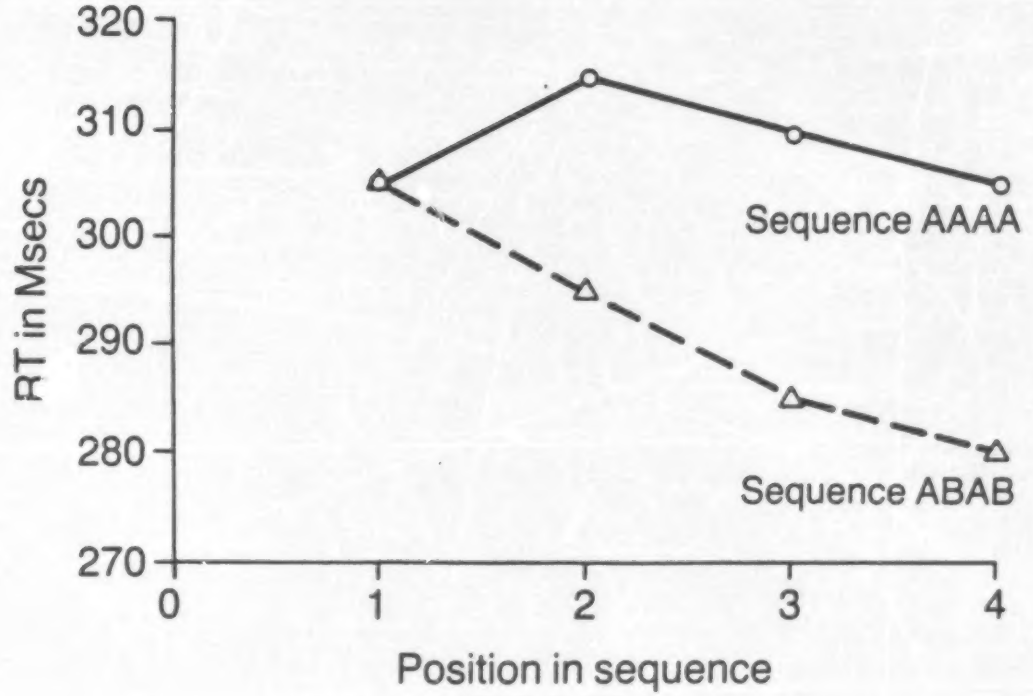

MODEL RSI = 0
5.0
4.6
4.2
3.8
3.3
2.9
2.5
# of cycles
Sequence ABAB
Sequence AAAA
0
1
2
3
4
Position in sequence

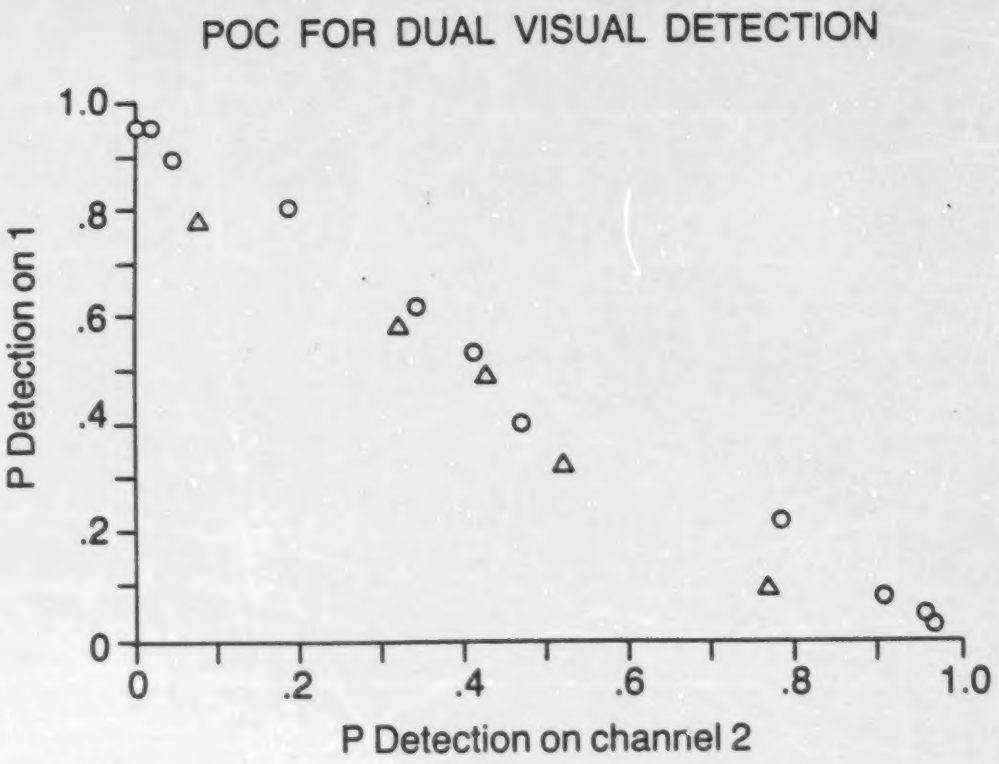

KIRBY DATA RSI = 50 MSECS
370
350
330
310
290
RT in Msecs
Sequence ABAB
Sequence AAAA
0
1
2
3
4
Position in sequence

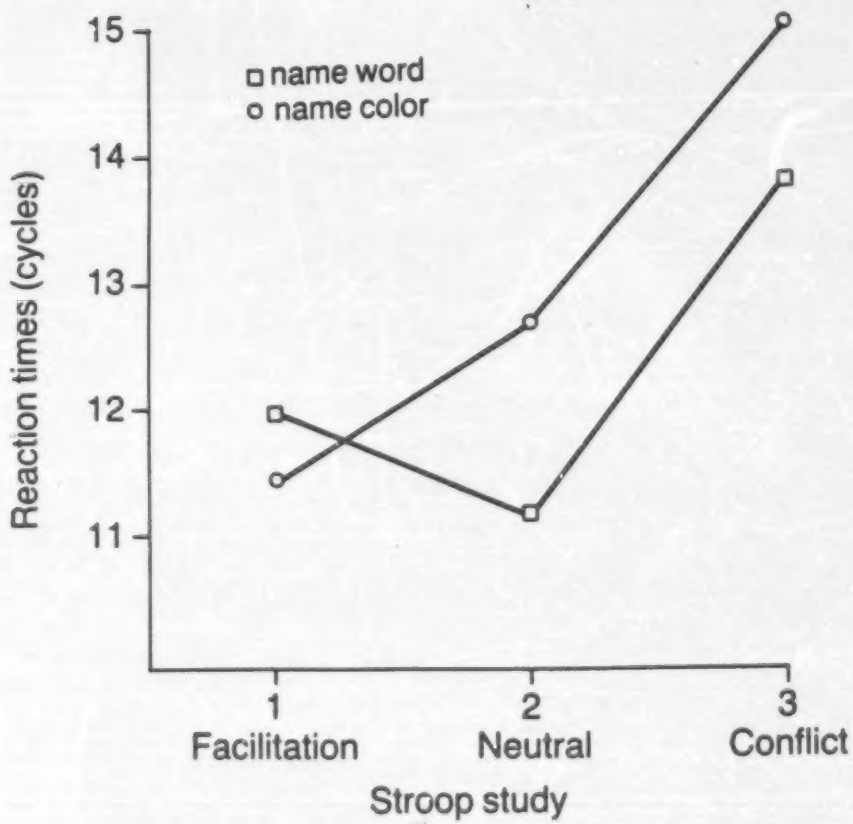
MODEL RSI = 6



KIRBY DATA RSI = 2000 MSECS




POC FOR DUAL VISUAL DETECTION
P Detection on 1
1.0
.8
.6
.4
.2
0
0
.2
.4
.6
.8
1.0
P Detection on channel 2


name word
name color
Reaction times (cycles)
15
14
13
12
11
1
Facilitation
2
Neutral
3
Conflict
Stroop study